A Balanced Adaptive Beamforming System for Broadband Wireless Communications

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***Abstract* — A broadband analog beamformer is realized in the form of balanced variable attenuators using PIN diodes. The phase deviation due to change in junction capacitance of a PIN diode with respect to applied voltage is improved by using a balanced architecture in the design of the variable attenuator. Measurement shows flat phase transition and linear attenuation over the frequency range from 2.5 GHz to 3.0 GHz, which can provide giga bit data throughput for QPSK modulated signal.**

I. Introduction

Adaptive beamforming systems are an attractive approach in wireless communication. They are known to enhance the interference reduction and power efficiency of the system. Although digital beamforming systems are getting popular due to the advance of digital technology, it is currently restricted to narrow band systems due to the limited DSP I/O and processing speed. When more bandwidth is required as the demand of wireless communications changes from low data rate to high rate multimedia data, an analog beamformer hybrid with DSP controller [1][2] is more advantageous with its high system throughput and advanced signal processing capability.

In this paper, we propose a broadband adaptive beamforming system based on the combination of a broadband analog beamformer and DSP control. This system consists of a millimeter wave RF front-end, an IF analog beamformer and a sub-band sampling scheme for DOA estimation to deal with broadband signal. Since realizing millimeter wave sources is often difficult, the adoption of sub-harmonic mixers and a sub-band sampling scheme can reduce the system complexity and cost. As the key building block of the beamforming system, the analog beamformer is designed in the form of quadrature weighting network of reflection-type variable attenuators. The balanced structure is implemented to compensate the phase error caused by parasitic components and non-ideality of the PIN diode devices over a wide frequency range.

This paper is organized as follows. First the system architecture for the adaptive beamforming system is introduced. Then design of a balanced broadband beamformer is described. With the measured beamformer characteristics, antenna beam patterns are synthesized and compared to the ideal patterns.

II. System Architecture

The proposed broadband beamforming system is shown in Fig. 1. In order to implement the broadband beamformer, there are several challenging issues: RF components in the frequency band must be able to accommodate broadband spectrum, speed of A/D converters to sample broadband signal, and weighting processes to apply weighting coefficients to signals.

First, the radio frequency is chosen to be at millimeter wave frequencies to meet broadband spectrum requirements. Thus, components of the RF receiver, including antennas and down converters should be

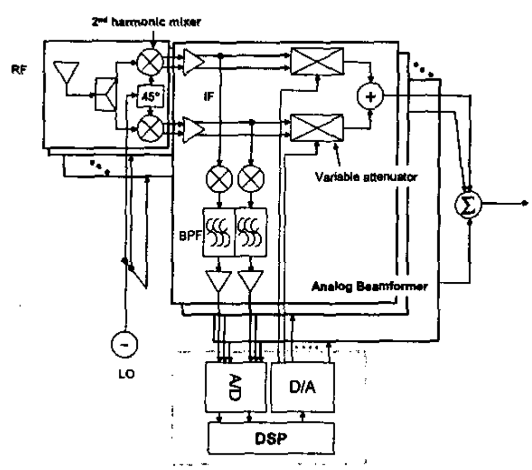

Fig. 1 Proposed broadband beamforming system structure.

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designed at millimeter wave frequencies. By using a second harmonic mixer for the downconverter, LO frequency can be lower, so that commercially available components can be used.

Secondly, unlike conventional beamforming systems which sample whole channel spectrum, it is proposed to use sub-band sampling techniques. Since bandwidth is broad, high sampling frequency of A/D converters is needed in order to sample whole bandwidth signal, this increases system costs. The sub-band sampling which samples only part of the signal spectrum makes the implementation of the system realizable.

Furthermore, it is very difficult to realize a high throughput digital signal processing system. Although the state-of-the-art DSP technology provides fast processing speed, data throughput processes is limited due to I/O speed restrictions. Thus, weighting processes in an analog domain is a low cost solution to relieve this constraint.

After downconverting RF to IF, IF signals split to sampling and weighting processes. For sub-band sampling, IF signal is downconverted to baseband again, and part of signal spectrum is selected using a narrow Band Pass Filter (BPF). Since most of signal spectrum is filtered out, amplification of filtered signal should be enough to sample at A/D converters. After the signal is sampled, conventional signal processing can be applied to estimate DOA and calculate weighting coefficients. Finally, the weighting coefficients are applied to signals in the broadband analog beamformer.

III. BROADBAND ANALOG BEAMFORMER

Since bi-phase attenuation is needed to apply complex weighting coefficients in I/Q vector formats, the broadband analog beamformer is realized in the form of well known reflection-type variable attenuators. Fig. 2 shows the Balanced Variable Attenuator (BVA) using PIN diodes in the proposed broadband beamformer. This BVA is implemented with an in-phase combiner and two variable attenuators that consist of a 90° hybrid coupler and two PIN diodes. The two PIN diodes are connected to the 0° and -90° ports of the 90° hybrid coupler. An input signal is reflected from the two ports according to the variable resistance values with respect to bias voltages. The reflected signals from two ports are canceled out at the input port and are added in phase at the isolated port. By changing the PIN diode resistance used to terminate the 90° hybrid coupler, the reflection coefficient varies from negative to positive values.

However, because of intrinsic and parasitic components of PIN diodes, the reflected signal from PIN diode has undesirable phase changes with bias and frequency changes. [3] used a linearizing analog circuit which control a D/A converter's reference voltage to compensate this error, but this is not enough to correct the parasitic reactance of PIN diode over several hundreds MHz bandwidth. In [4], a QAM vector modulator using Lange couplers and cold-pHEMTs as variable resistor components has been developed with balanced structure to compensate the inherent shunt capacitance at millimeter wave frequency.

In Fig.2, the BVA is required to have a 0° and 180° phase input signals and a complementary voltage set to control PIN diode sets. By connecting the inputs to a differential mixer used for down converting, a 180° hybrid coupler is not necessary and constant phase difference can be achieved over a wide frequency range. This balanced structure can compensate monotonic reactance changes of the PIN diodes in broadband range. This is done by applying a complementary voltage set which is selected to generate complementary phases and attenuation levels for the pair of variable attenuators. These outputs are summed

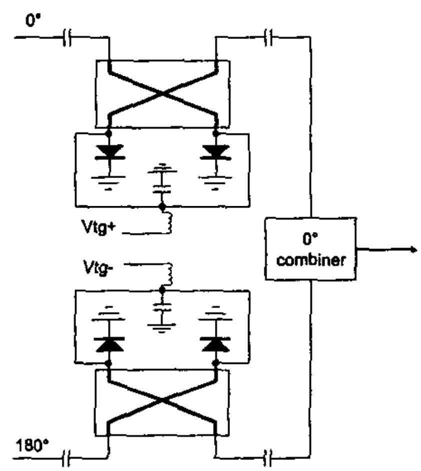

Fig. 2 Balanced Variable Attenuator (BVA).

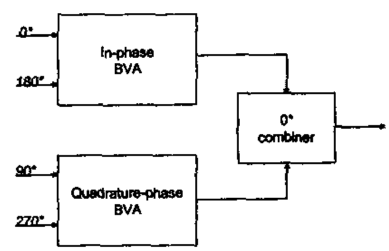

Fig. 3 Quadrature weighting network.

using an in-phase combiner to produce a linearized output.

Fig. 3 shows one complete variable attenuator constructed with two BVAs. By changing attenuation of I/Q signals and recombining them, the amplitude and phase of the signals can be controlled. Since the proposed beamformer system adopts quadrature mixers, 90° hybrid coupler does not need to generate I/Q signals. The inputs (0° and 180°, 90° and 270°) of each I/Q BVA, are connected from differential mixer outputs. The two complementary voltage sets (vtg+ and vtg-) are applied to in-phase and quadrature-phase BVAs separately, so that 180° out of phase signal can be combined with 0° phase signal canceling out phase deviations corresponding to intrinsic and parasitic components.

In order to investigate BVA beamforming performance, BVAs are implemented using Agilent Technologies HPND-4038 PIN diode and Anaren 11306-3 90° hybrid coupler. Transmission S-parameter (S21) is measured using a network analyzer. For this measurement purpose, extra phase shifters are used to keep phase difference at input of variable attenuators. The vtg+ and vtg- are controlled by 8bit D/A converters connected to a PC, and S21 is measured under each voltage condition.

Fig. 4 shows attenuation levels and phases of sampled points in polar forms at 2.5 GHz and 3 GHz, which correspond to the edges of the operational band. In this measurement, only 19 × 19 (361) points are sampled. In reality, although 8bit D/A (256 points) converters are used, one branch (in-phase or quadrature-phase) voltage set has 192 points. This was done because the BVA control voltage was offset in order to make attenuation symmetric. The total controllable points are 192 × 192 (36864) points. The measurement results show linearized attenuation and phase changes, but slight phase deviations at control voltage limits can be noticed. These errors can be corrected using look-up table method [3].

IV. Synthesized Beamforming Results

Fig. 5 shows the synthesized beamforming results using measured data from the BVA. In this calculation, an eight

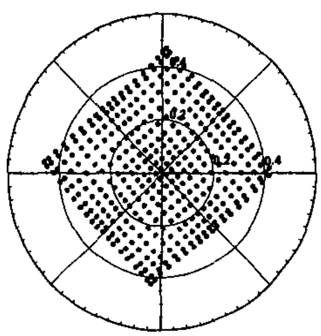

Fig. 4 (a) S21 measurement with respect to I/Q attenuation at 2.5 GHz.

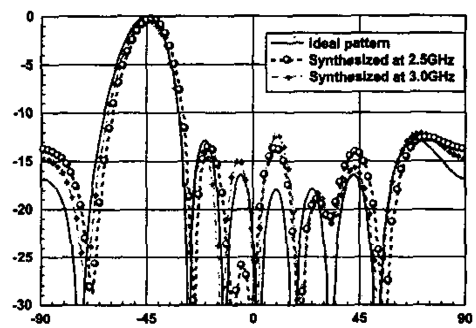

Fig. 5 (a) Synthesized beamforming patterns towards -45°.

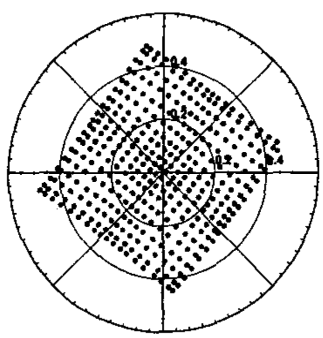

Fig. 4 (b) S21 measurement with respect to I/Q attenuation at 3.0 GHz.

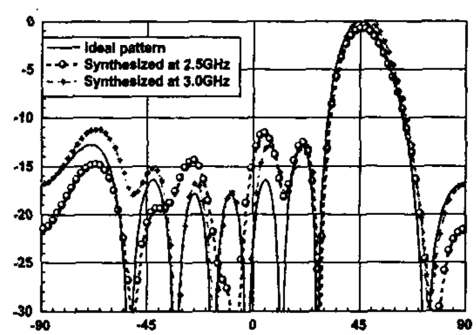

Fig. 5 (b) Synthesized beamforming patterns towards +45°.

element array is considered. Weighting coefficients are calculated from assumed incident angle, then attenuation values corresponding to weighting coefficients for in-phase and quadrature-phase branches are calculated. The closest data to these attenuation values out of 361 sampled points are selected for each variable attenuator.

The synthesis of beamforming is performed at several angles from -45° to +45° and two results are shown for the edge of this scanning range. The main lobe is squinted towards broadside and several sidelobe levels are 5dB higher than ideal patterns in the worst case. This is caused by quantization errors of the D/A converters as well as residual errors from difference between real attenuation value and sampled attenuation value. These errors can be minimized if the voltage of D/A converters are selected in full bit resolution. Comparing synthesized beam patterns at 2.5 GHz and 3 GHz, 500MHz of operation bandwidth of BVA is acceptable.

V. CONCLUSION

In this paper, a broadband beamforming scheme using balanced variable attenuators is proposed. Using a balanced structure for the variable attenuators, phase consistency of weighting processes of analog beamformer is obtained from 2.5 GHz to 3.0 GHz. Furthermore, synthesized beamforming patterns within the bandwidth matched to ideal patterns well. The sub-band sampling circuits are currently under investigation.

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